PREDICTION OF FRAGMENT RANGE FOR RESPONDING MAGAZINES BASED ON THE BAKHTAR EXPLOSIVES SAFETY CRITERIA

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ABSTRACT

An innovative and cost effective method is presented for prediction of hazardous fragment range resulting from accidental detonation in an underground explosives storage magazine. The approach is unique in terms of its formulation and data requirements. It is formulated by defining two new terms namely; **dynamic response factor (R)** and **load capacity factor (C)** describing the characteristics of the engineered and geologic systems. The required site specific data are obtained by performing non-destructive index tests on the geologic and engineered systems in the field. This work is an extension of the Bakhtar Explosives Safety Criteria developed for storage of explosives in underground structures. The verification of the empirically formulated approach has been done through a series of scaled model tests conducted under the normal gravity (1-g). The research was sponsored through the Department of Defense SBIR Phases I and II programs under contract with the United States Air Force. The formulated criteria and associated characterization methodology can also be used for siting, loading density optimization, site selection, site investigation to determine communication between adjacent magazines, estimation of required depth of rock cover for a given loading density, safe design and construction of underground munitions storage magazines.

1. BACKGROUND

Protection of personnel, property, and equipment is the main concern to the DOD and other government agencies for their ammunition storage program. The review of available reports and standards, documented on assessment of hazards associated with a given situation, lead to identification of five principal effects of explosion hazards (DOD 6055.9 STD); namely:

(1) Blast Pressure

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1994**	2. REPORT TYPE	3. DATES COVERED **00-00-1994 to 00-00-1994**
4. TITLE AND SUBTITLE **Prediction of Fragment Range for Responding Magazines Based on the Bakhtar Explosives Safety Criteria**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Bakhtar Associates,2429 West Coast Highway, Suite 201,Newport Beach,CA,92663**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM000767. Proceedings of the Twenty-Sixth DoD Explosives Safety Seminar Held in Miami, FL on 16-18 August 1994.**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**28**	

(2) Fragments
- Primary
- Secondary

(3) Thermal Hazards

(4) Chemical Hazards

(5) Ground Shocks

Extensive studies have been performed in the past on hazardous effects of blast pressure, induced chemical and thermal environments, and ground shocks. However, the degree and extend of fragment induced hazards associated with the accidental detonation of explosives stored in sub-surface rock/soil structures are still not fully verified.

Generally speaking, the sub-surface facility used for storage of explosives consists of a geologic system with the associated features (joints, discontinuities, etc.) and engineered system with the associated structural components (tunnel, chamber, support liner, etc.). The geologic system act as the host for the engineered system (magazines) which depending on their spatial locations and designs can be either "responding" or "non-responding" structures. The "responding" magazines are those underground structures in which accidental detonation of the stored explosives causes the cover rock to break into fly-rock. The "non-responding" magazines are those that upon accidental detonation the structural integrity of cover rock stays intact and blast-induced damages are localized in their extend. For the responding magazines, characteristics of the geologic system and the dimensional characteristics, including thickness of rock cover, of the engineered system influence the fragment throw-distance. Observations made from the China Lake Tunnel Explosion Tests (Halsey et al., 1989), US Air Force Scale Model tests (Bakhtar 1993a), and the Swiss Steingletscher accident (Bakhtar, 1994) revealed that support liner characteristics do not greatly influence fragment throw-distance for responding magazines. The insignificant influence of the liner characteristics on the blast-induced fragments can be attributed to the following reasons:

- High loading density of storage chamber or magazine.

- Continuous rapid build up of high internal pressure within chamber with delayed venting producing loads several magnitudes higher than the tensile strength of liner materials.

- Low dynamic tensile strength property of reinforced cementitious materials compared to rock strength and gravity load.

The US DOD standards for explosive safety, commonly referred to as "DOD6055.9 STD" is used to determine the damage or injury potential of explosion induced fragments, for responding magazines, based on the distance prevailing between the "potential explosion site" (PES), the "exposed site" (ES), and

- ability of PES to suppress the blast overpressure;
- ability of ES to resist the explosion effects.

For explosives stored in facilities constructed in rocks, the current Q-D relationships are based on the cubic-root expressions. The cubic-root relationships appear to be too general and do not account for the site specific characteristics of the geologic and engineered systems. Results of more than three decades of studies conducted on detonation tests in confined or partially confined sub-surface chambers reaffirm the importance of characteristics of the geologic and engineered systems on the hazardous effects of explosive outputs listed above. The influence of material properties of the geologic system on the various components of explosives output from underground tests are discussed by many researchers such as Bakhtar (1989), Crowley (1973), Fogel, et al. (1985), Labreche (1983), and Lampson (1946).

The blast-induced debris resulting from accidental detonation of a responding magazine are classified into

- Primary Fragments
- Secondary Fragments

Primary fragments are produced when cased donors and explosive containers shatter. These fragments have small sizes and very high initial velocities (at the order of 1000s ft/sec) depending on the thickness of the metal container, explosive type (spherical, cylindrical, or prismatic), the shape of the end or middle of the container (conical, oval), etc. Several expressions have been provided in the report TM55-1300 for the initial velocity and number of fragments associated with a given donor casing.

Secondary Fragments are produced as a result of high blast pressure on the structural components and cover rock, they are larger in size than the primary fragments, and travel initially at velocities on the order of hundreds of feet per second. The US DOD standards further defines a hazardous fragment as one having an impact energy of 58 ft-lb (79 joules).

Study reported by Bakhtar (1993b) highlights the influence of the air drag coefficient on the velocity of the primary fragments. However, for the secondary fragments during the post blast phase, the fragmented rock mass moving in air is compacted resulting in the specific load to increase and consequently decrease the effects of air drag. Furthermore, additional crushing of fragments take place by the kinetic energy of flight and the potential energy upon impact on the ground. Theoretical predictions can be made based on the Energy Balance Equation and the constitutive relationships between the kinetic energy and differential stiffness coefficient at impact representing that part of energy utilized for crushing. However, such studies are extremely hard to perform and verify because of many difficulties involved in planning and extremely high cost associated in conducting prototype tests on responding magazines.

Because of the difficulties encountered in conducting prototype tests on responding sub-surface magazines the need for alternative approaches such as scale model tests based on physical modeling, under normal and elevated gravity, becomes apparent. The advantage with the physical modeling tests is that if the static and dynamic similitude conditions are preserved between the prototype and its model, the results obtained from the small scale tests can be used to predict the prototype behavior. Furthermore, the scale model tests can be conducted under controlled conditions allowing researchers to investigate the influence of various parameters on the simulated event. A recent survey of western and eastern literature on scale model tests and scaling laws is provided in a report by Bakhtar (1993b).

This paper describes how a series of scale model tests was performed to simulate the prototype tunnel explosion test conducted in China Lake California in 1988 (Halsey, 1989). The test results are used to develop an empirical mathematical relationship which by accepting site specific data on the characteristics of the geologic and engineered systems provides a direct correlation between the fragment range and loading density. The unique applications of this criteria and its associated site characterization methodology are listed below:

- Prediction of hazardous fragment range based on a given loading density for accidental detonation of a responding magazine.

- Estimation of TNT equivalent weight of stored explosives based on the observed hazardous fragment range originating from a responded magazine.

- Optimization of loading density based on the site specific characteristics of the geologic and engineered systems for a responding magazine.

- Prediction of the required depth of cover for a magazine to become "non-responding" for a given loading density and site specific characteristics of the geologic and engineered systems.

- Estimation of the required width of "pillar" to prevent communication between adjacent magazines.

- Establishing the required specifications for siting a magazine.

2. BAKHTAR EXPLOSIVES SAFETY CRITERIA

The functional form of the Bakhtar Explosive Safety Criteria was presented at the DDESB 25th Explosives Safety Seminar, Bakhtar (1992), for assessment of quantity-distance (Q-D). Based on this formulation, development of a reliable safety criteria for storage of explosives is contingent on the ability to characterize and assess the site specific characteristics of the **engineered** and **geologic** systems. For the Q-D formulation, initially five parameters of the geologic/engineered systems were identified as pertinent to such assessments. They included: equivalent stiffness characteristics of the two systems, loading density of the chamber, seismic wave velocity in the geologic system, and venting characteristics of the engineered system. Experience gained during the recent scaled-model tests conducted for the U.S. Air Force (Bakhtar, 1993b), coupled with the observations at the Swiss Steingletscher Accident site (Bakhtar, 1994), prompted the Principal Investigator to introduce additional terms into the criteria; namely: thickness of overburden at the chamber location and the gravity term "g". These parameters are combined into a single functional form which provides a more complete expression for the (Bakhtar 1992) formulation:

$$\boldsymbol{D = f(E^a,\ Z^b,\ Zc,\ Sd,\ V^e,\ gf)}$$

where:

D	=	distance, m (ft) ;
E	=	equivalent stiffness characteristics of geologic system, MPa (psi);
K	=	loading density, kg/m^3 (lb/ft^3) ;
Z	=	overburden thickness above chamber, m (ft);
S	=	venting characteristics of the engineering system, m^2 (ft^2).
V	=	P-wave velocity in geologic system, m/sec (ft/sec);
g	=	gravity, m/sec^2 (ft/sec^2).
		a, b, c, d, e, f = constants.

The seven parameters chosen to describe the Bakhtar's formulation are easily obtained in the field as described by Bakhtar (1989), Bakhtar and Jenus (1994). Dimensional analysis technique or Buckingham Pi theorem can be used to derive the final form of the Equation (1).

It is important to note that translation of the functional form of Equation (1) into an empirical mathematical expression can only be possible by conducting enough experiments under controlled conditions to enable constants a, b, c, d, e, and f to be determined. The five constants in Equation (1) imply that five sets of tests would be required. If we consider that for each test two of the parameters are kept unchanged, then the combination of two constants from six variables require at least fifteen tests to be conducted to yield statistically reliable results. In order to simplify the large number of required tests two new terms are defined in this paper which facilitate the ease of analyses and reduce the minimum number of required experiments using the 'physical modeling" technique.

3. PHYSICAL MODELING

3.1 GENERAL

Physical modeling, based on geometric scaling, has been practiced by the underground miners throughout the world since 18th century. Many researchers studied the applications of scale models in geomechanics and proposed theoretical and experimental procedures for physical modeling of soil and rock. A series of documents cited under Sir Archibald Geikie (1897) and Sir James Hall (1912) and others indicate the interest which existed among the pioneering geologists in understanding the mechanics of the earth by using model materials. Russian and European researchers have been performing physical modeling since 1900 for deign of structures in civil, mechanical, and mining engineering fields. Russian scientists have been conducting experiments at high gravity, using centrifuge technique, and at normal gravity, using scaled modeling technique. However, with the advent of computers, the numerical modeling gradually became more popular than the physical modeling in geomechanics and structural engineering.

Centrifuge modeling using prototype material has become popular for the last three decades. However, physical modeling using synthetic material with appropriately scaled properties is not a common technique. Research organizations, universities and government laboratories have been using sophisticated numerical modeling techniques to predict the behavior of surface and underground structures. With the growing interest in utilizing the subsurface facilities for both military and civilian purposes, the long-term performance as well as load response of such structures are becoming of interest to the scientists and engineers. The need to assess the performance of underground structures and requirements for calibrating the numerical codes has renewed interest in the field of physical modeling based on scale-model testing under normal gravity.

The most important initial step in planning a physical modeling experiment is the identification of the pertinent parameters. In many cases, economic constraints, limitation of testing facility, and nature of the investigation control the choice of the model. However, results of almost two decades of research (Bakhtar, 1993b) indicate that physical modeling in geomechanics and structural engineering maybe perform under 1-g by choosing two different approaches as outlined below:

(1) **Material scaling** - in which the geometry and strength related properties of the model materials are scaled. In such cases, the load required to cause deformation in the model must be reduced in order to maintain the similitude conditions with its prototype.

(2) **Replica Scaling** - in which the geometry is scaled, however, the strength related properties of the model material are matched with those of its respective prototype. In such cases, the required load to cause deformation in the model must be increased to maintain the similitude conditions with its prototype.

The emphasis in this paper is directed towards adherence to the theory and application of the scale-model testing under normal gravity (1-g) using the material scaling approach. Based on the author's more than 20 years of experience; the replica scaling is, by and large, more costly and in many cases its application becomes distorted in geomechanics and structural engineering during the construction phase of models.

Also, centrifuge testing has limited applications in modeling geologic system in which structural features (joints, discontinuities, etc) as well of the characteristics of the engineered system are important parameters for modeling. However, centrifuge technique maybe used for component testing of a discrete part of a prototype structure.

3.2 SIMILITUDE CONDITIONS

The derivation of the general theory of similarity between a rock model and its prototype can best be discussed in terms of a purely mechanical system. Complete mechanical similarity requires that conditions of geometric and dynamic similarities be satisfied between a model and its prototype within the range of loading of interest in a particular investigation. **Geometric similarity** means that the model is true to scale in length, area, and volume. **Dynamic similarity** means that the ratios of all types of forces are equal. These forces result from inertia, gravity, viscosity, elasticity (fluid compressibility), plasticity, surface tension and pressure. Magnetic forces are not considered for investigations of interest to blast loading. It can be argued that complete mechanical similarity also requires kinematic and thermal similarity, which is not discussed in the present paper. However, it is the author's opinion that within the scope of most experimental investigations, dynamic similarity coupled with geometric similarity provide the necessary provisions for solving problems related to the load response of geologic and engineered systems.

Pertinent variables for modeling an elastic-brittle rock to failure initiation are length, stress, unit weight, angle of internal friction, modulus of elasticity, Poisson's ratio, and time. By modeling all or a selected numbers of these parameters, the researcher will have the necessary tools for studies related to performance and load response (static or dynamic) of structures designed in a rock mass.

For static problems, only two fundamental dimensions are involved, namely: force "F" and linear dimension "*l*". The similitude requirements that govern the dynamic relationships between the model and its prototype structure depend on the geometric and material properties of the structure and on the type of loading. In general, the dynamics of any structure are governed by an equilibrium balance of time-dependent forces on the structure. These are the inertia forces that are the product of the local mass and acceleration, the resistance forces that are a function of stiffness of the structure in the particular direction in which motion is occurring, and the energy dissipation of the damping forces, whether material or construction related.

For modeling structures in rock mass, the following basic conditions of similarity must be satisfied:

- **Geometric Similarity** - requires the ratio of the distance between any two points in the prototype to the corresponding distance in its model to be constant.

- **Kinematic Similarity** - requires that the movement of particles in the model follow those of its prototype with respect to time and space.

Geometrically and kinematically similar structures are dynamically similar if the ratios of various similar mechanical forces that act on any two corresponding particles in the prototype and its model are constant. These parameters are those of elastic, plastic, viscous, gravity, inertia, and friction related forces. Assuming F^* is the force scale factor, the above conditions can be mathematically represented by:

$$\frac{(F_g)_m}{(F_g)_p} \quad \frac{(F_i)_m}{(F_i)_p} \quad \frac{(F_v)_m}{(F_v)_p} \quad \frac{(F_e)_m}{(F_e)_p} \quad \frac{(F_f)_m}{(F_f)_p} \quad = \quad F^*$$

where:

F_g = Gravity Force

F_i = Inertia Force

F_v = Viscous Force

F_e = Elastic Force

F_f = Friction Force

It should be pointed out that in this section the general theory of similarity between a model and its prototype for a purely mechanical system is discussed. Thermal properties are important parts of similarity modeling in geomechanics. However, the emphasis in our discussion is on application of physical modeling for scale-model testing of structures in rock not dynamic treatment of tectonic evolution. For the later, an excellent treatise by Ramberg (1967) and Hubbert (1937) are available as possible references. Therefore, the similitude conditions are discussed by using the KLOTZ Tunnel tested in China Lake (Halsey, et al. 1989) as the prototype and constructing its 1:20th model - US Air Force Scaled-Model Experiments (Bakhtar, 1993b). Furthermore, results of model tests, which form the basis for the Bakhtar Explosives Safety Criteria, are compared with those from the prototype to show the applicability of the modeling approach and the predictive capabilities of the formulated empirical expression.

The derivation of similarity conditions between a prototype and its model can be shown based on "stress equation of motion" and the "conservation of angular momentum" (Bakhtar, 1993b). The mechanical properties of the model can be completely specified, if the properties of its prototype are known, in terms of the fundamental scale factors mass (m^*), length (ℓ^*), and time (t^*). Several scale factors of interest for model testing, relating mechanical properties of the model to those of its prototype, are shown in Table 1. The remaining scale factors can be derived using the fundamentals of mechanics as discussed by Bakhtar (1993b).

TABLE 1 - SCALE FACTORS FOR MECHANICAL QUANTITIES*.

Quantity	Dimensional Form	Scale Factor[⊘]
Linear Dimension	L	ℓ^*
Area	L^2	ℓ^{*2}
Volume	L^3	ℓ^{*3}
Density	ML^{-3}	$m^* \ell^{*-3}$
Time	T	$\ell^{*1/2}$
Stress	$ML^{-1}T^{-2}$	$m^* \ell^{*-2} = m^* \ell^{*-1} t^{*-2}$
Force	MLT^{-2}	$m^* \ell^* t^{*-2} = m^*$
Velocity	LT^{-1}	$\ell^{*1/2}$
Acceleration	LT^{-2}	$\ell^* t^{*-2} = 1$
Angular Velocity	T^{-1}	t^{*-1}
Mass	M	$m^* = \rho^* \ell^{*3}$
Energy+	ML^2T^{-2}	$m^* \ell^{*2} t^{*-2}$
Impulse	MLT^{-1}	$m^* \ell^* t^{*-1}$
Strain	LL^{-1}	1
Friction Angle	L^0	1
Poisson's Ratio	$\Delta l_1/L_1/\Delta l_2/L_2$	1
Frequency	T^{-1}	t^{*-1}
Curvature	L^{-1}	ℓ^{*-1}

* - For Material Scaling Under 1-g.
\+ - Same Scaling Relationship Applied to Impact Energy of Fragments
⊘ - Scale Factor = $\{\text{Characteristic}\}_{\text{prototype}}/\{\text{Characteristic}\}_{\text{model}}$

TABLE 1 - SCALE FACTORS FOR MECHANICAL QUANTITIES*.

3.3 PROTOTYPE CHARACTERISTICS

The engineering and geologic characteristics of the KLOTZ Tunnel, tested in China Lake (Halsey, et al., 1989), are used as the prototype to describe the Air Force Scaled-Model tunnel explosion tests. As mentioned previously, the first step in physical modeling is identification of the pertinent parameters to be modelled. Our goal is the simulation of the KLOTZ Tunnel explosion event. Therefore, pertinent parameters of the geologic and engineered systems which impact such event should be identified during the planning stage. These information are subsequently used for

- Investigation of Appropriate Scale
- Selection of Test Site
- Formulation of Required Mix Proportion for Model Material

Tables 2 and 3 provide general information on the pertinent characteristics of the geologic and engineered systems.

TABLE 2. ENGINEERED CHARACTERISTICS OF PROTOTYPE TUNNEL.

PROTOTYPE KLOTZ TUNNEL TESTED IN CHINA LAKE, CALIFORNIA (1988)
CHAMBER Shotcrete with Wire-Mesh Lining
5-m wide x 4-m high x 18-m long (16.4-ft x 13.1-ft x 59.1-ft)
TUNNEL Concrete Portal with Concrete/Shotcrete Wire-Mesh Lining
2.4-m wide x 2.4-m high x 25-m long (8-ft x 8-ft x 82-ft)

TABLE 2.
ENGINEERED CHARACTERISTICS OF PROTOTYPE TUNNEL.

TABLE 3. OVERALL CHARACTERISTICS OF GEOLOGIC SYSTEM.

CHARACTERISTICS	RANGE OF NUMERICAL VALUES	AVERAGE
Joint Roughness Coefficient (JRC)	2 - 6	4
Block Length (L_n)	17 in (0.43 m) - 22 in (0.56 m)	20 in (0.51 m)
Laboratory Sample Size (L_o)*	3.94 in (0.10 m)	3.94 in (0.1 m)
Joint Wall Compression Strength (JCS_o)	2310 psi (15.9 MPa) - 9000 psi (62.0 MPa)	4695 psi (32.4 MPa)
Effective Normal Stress on Joint (σ'_n)	0.29 psi (0.002 MPa) - 32 psi (0.22 MPa)	12.90 psi (0.089 MPa)
Smooth Hydraulic Aperture (e_o)	0.011 in (0.279 mm) - 0.017 in (0.432 mm)	0.014 in (0.355 mm)
Residual Friction Angle (ϕ_r)	19° - 25°	21.6°
Basic Friction Angle (ϕ_b)	30°	30°
Unconfined Compressive Strength of Intact Rock (Schmidt Hammer) σ_c	5715 psi (39.41 MPa) - 16,132 psi (111.25 MPa)	10310 psi (71.11 MPa)
Joint Strikes	N38°E - N60°E	N52°E
Joint Dips	48° - 90°	67°
Q-Values	0.65 - 1.30	≈1.0

* - Corresponds to the length of profile gage.

TABLE 3. OVERALL CHARACTERISTICS OF GEOLOGIC SYSTEM.

3.4 MODEL TUNNELS

The prototype data presented in Tables 2 and 3, were used to construct a series of five scaled model tests at 1:20th scale to verify the applicability of physical modeling for simulation of the Tunnel Explosion Test and validate the Bakhtar Explosives Safety Criteria. The applications of the Bakhtar Explosives Safety Criteria are directed towards assessment of hazardous range of the blast-induced fragments from accidental detonation of a responding magazine.

Because of the scale of investigation, modelled geologic and engineered systems were cast in a series of five trenches excavated to accommodate the required volume. Extensive investigations were made to match the impedance characteristics of the cast in-place model materials and those of the host native ground for realistic ground shock simulation. Locations of the test beds were excavated, approximately 100-m (300-ft) apart, in an sloping ground to yield a final surface profile similar to that of the prototype.

A mix proportion, with ingredients listed in Table 4, was formulated to yield a material model refer to as the "rock-simulant" which upon curing possessed a similar characteristics as those of the natural rock at a scale of Prototype/Model = 20:1. Extensive quality control (QA) and quality assurance (QC) procedures were implemented during material characterization tests for the formulated rock-simulant and subsequent casting of each test bed. A step-by-step casting procedure was employed to simulate the geologic discontinuities. Table 5 shows the overall dimensions of the prototype and its model structures at the 1:20th scale.

TABLE 4. MIX FOR MODEL MATERIALS

INGREDIENTS
Water with Dye and Coloring Agents
Portland Cement Type I and II
Aquagel Bentonite
Baroid Barite
Glass Beads (#12)
An Air entraining Agent (AMEX 210)

TABLE 4. MIX FOR MODEL MATERIALS

Dye and coloring agents were added to the water during mixing procedure of the various pour to differentiate between various rock layers and the depth (elevation) from which ejecta is originated. For models, the simulated engineered systems were constructed with a fast setting plaster based material about 1-cm (0.4-in) thick and fine wire-mesh screen. Figure 1 shows a typical sectional view through the center of a test bed.

TABLE 5. MODEL DIMENSIONS AT 1:20th SCALE

PROTOTYPE DIMENSIONS	MODEL DIMENSIONS
CHAMBER	CHAMBER
5 m wide x 4 m high x 18 m long (16.4 ft wide x 13.1 ft high x 59.1 ft long)	0.25 m wide x 0.20 m high x 0.90 m (10 in wide x 8 in high x 35 in long)
TUNNEL	TUNNEL
2.4 m wide x 2.4 m high x 25 m long (8 ft wide x 8 ft high x 82 ft long)	0.12 m wide x 0.12 m high x 1.2 m (5 in wide x 5 in high x 50 in long)

TABLE 5. MODEL DIMENSIONS AT 1:20th SCALE

3.5 EXPLOSIVES SCALING

The explosive material used for the KLOTZ Tunnel test consisted of pelletized, reclaimed composition B packaged in 22.7 and 27.2 kg (50- and 60-lb) cardboard boxes. The total weight of composition B explosive used was 20,003.8 kg (44,100 lb) placed at the center of the chamber.

For the TNT equivalent (1.1 equivalence factor), the corresponding weight is 22,004.18 kg (48,510.4 lb). The resulting loading density is calculated to be:

$$(\text{LOADING DENSITY})_{\mathbf{PROTOTYPE}} = \frac{\text{Net TNT Explosives Weight}}{(\text{Volume of Prototype Chamber})} \qquad (3)$$

$$= 22{,}004.18/332 = 66.4 \text{ kg/m}^3$$

The loading density for the model structure should have the same value

$$(\text{Loading Density})_{\mathbf{model}} = (\text{Loading Density})_{\mathbf{prototype}}$$

or

$$66.4 = \text{(Net TNT Explosive Weight)/(Volume of Model Chamber)}$$

$$\text{(Net TNT Explosive Weight)}_{model} = 66.4 \text{ x } (0.25 \text{ m x } 0.2 \text{ m x } 0.9 \text{ m})$$

or

$$\text{(Net TNT Explosive Weight)}_{model} = 2.988 \text{ kg } (5.068 \text{ lb}), \text{TNT}$$

The TNT equivalence factor for the composition C-4 plastic explosive is 1.35 under normal density and void ratio, therefore, the equivalent weight for C-4 is calculated as follows:

$$\text{(Net Explosive Weight)}_{model} = 2.988/1.35$$

$$= 2.213 \text{ kg } (4.880 \text{ lb}), \text{ C-4 Plastic Explosive.}$$

Similarly if the Composition B is used, the TNT equivalence factor of 1.1 can be used to calculate the required weight for the scaled-model test as

$$\text{(Net Explosive Weight)}_{model} = 2.988/1.1$$

$$= 2.716 \text{ kg } (5.986 \text{ lb}), \text{ COMP-B Explosive.}$$

It should be noted that properties of explosives change drastically as the density and void ratio of these chemical compounds are changes. For discussion presented above, idealized conditions for explosives are assumed. Furthermore, the fabricated charge is assumed to be cylindrical to facilitate the ease of emplacement and complete detonation is achieved by attaching a booster and EBW to the explosive charge.

FIGURE 1. SECTIONAL VIEW THROUGH A TYPICAL TEST BED.

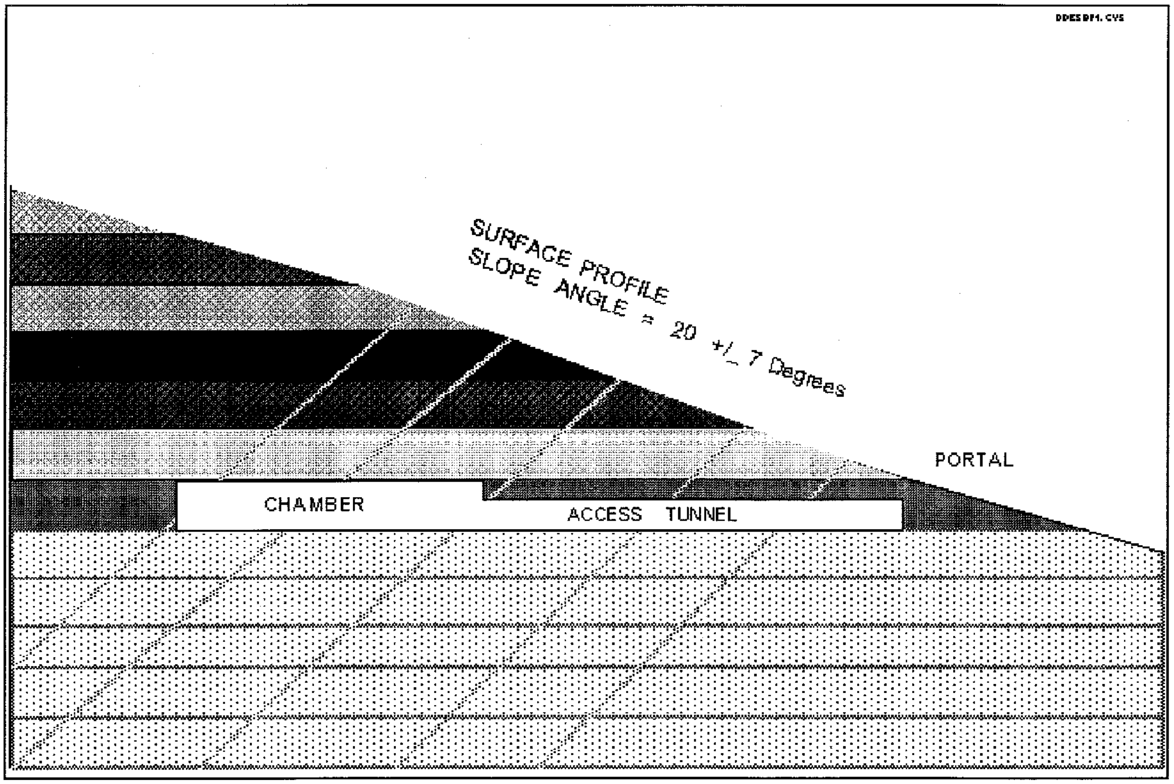

FIGURE 1. SECTIONAL VIEW THROUGH A TYPICAL TEST BED.

3.6 FRAGMENTS

Recovery of the blast-induced fragments constitute the most important part of the investigation. For the model tests, fragment recovery tasks were performed within a long segment stretching from the portal at ±20° along the extended tunnel axis. Scaling relationship shown in Table 1 were used to determine the hazardous size of a model fragment. Cut-off distances were based on model fragment size of 1.3-mm (0.05-in) which corresponds to a maximum impact energy of 58 ft-lb (79 joules) in the prototype.

It is important to note that large pieces of debris were found behind the fragment recovery area at short distances as depicted in Figure 2.

FIGURE 2. DEPICTION OF FLY-ROCK PATHS.

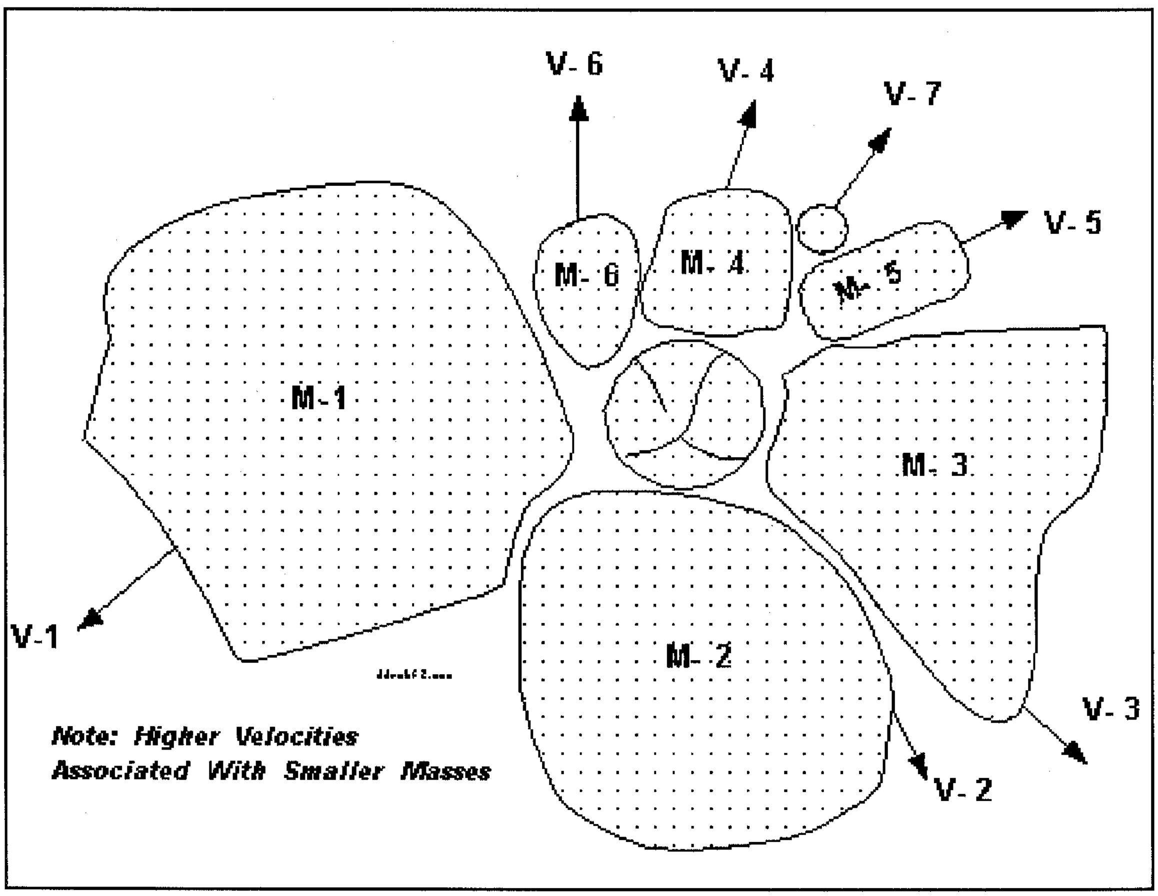

FIGURE 2. DEPICTION OF FLY-ROCK PATHS.

4. APPLICATION OF DIMENSIONAL ANALYSIS

4.1 GENERAL

The fragment recovery data coupled with information on characteristics of the engineered and geologic systems are used to obtain a mathematical expression based on the functional form of the formulated Bakhtar Criteria presented in Equation (1). By and large, mathematical formulation and subsequent solution of engineering problems is contingent on our ability to define the complex interaction between the variables involved. Analytical and computer models use various approximation methods to bridge the gap between the variables and find the best possible solutions. Parametric studies of the pertinent variables may lead to definition of the upper and lower bonds of approximate solutions. In certain cases where variables influencing the phenomenon are discretely identifiable, the method of "dimensional analysis" can be applied to arrive at the solution of the problem. This technique is based on the principle that meaningful physical relationships between quantities must be dimensionally "homogeneous"; that is, both sides of an equation must have the same dimensions.

The first step in using the dimensional analysis technique is to select the fundamental or primary dimensions. Usually, mass, length, time, and temperature are used as the primary dimensions and other are derived based on these variables. Newton's Second law is extensively used for such analysis. Dimension conversion factor (g_c) and energy conversion factor (J) may be required to be introduced into the final results based on the primary dimensions noted above.

The second step is to write a functional relationship between the dependent variable (y) and independent variables (x_i).

$$y = f(x_1, X_2, X_3, ..., X_n) \tag{4}$$

The function represented in the Equation (2) can be expressed as an exponential series

$$y = C_1 x_1^{a_1} x_2^{b_1} x_3^{c_1} \ldots x_m^{z_1} + C_2 x_1^{a_2} x_2^{b_2} x_3^{c_2} \ldots x_m^{z_2} + \tag{5}$$

The quantities C_i, a_i, b_i,......z_i in Equation (3) are the unknown constants.

Dimensional analysis tests the general form of equations that describe natural phenomena. Applications of dimensional analysis abound in nearly all fields of engineering, particularly, in dynamics, fluid mechanics, and heat transfer theory. A systematic and thorough treatment of the principles of dimensional analysis is provided by Langhaar (1983).

4.2 BAKHTAR FORMULATION OF EXPLOSIVE CHARGE - FRAGMENT RANGE CRITERIA

Field acquisition of variables shown in Equation (1) can lead to completely define the characteristics of the geologic and engineered systems. It is strongly believed that those variables listed in Equation (1) are the only parameters that can directly influence the phenomena associated with induced fragments resulting from accidental detonation of a responding magazine.

Final form of the Equation (1) may be derived using the Buckingham's Pi Theorem or dimensional analysis in which the dimensions of the various parameters are related to the fundamental dimensions, length (L), time (T), and mass (M) through the Newton's 2nd. Therefore,

$$E = \frac{Force}{Area} = [\frac{ML}{L^2T^2}] = [\frac{M}{LT^2}] \tag{4}$$

$$K = \frac{Weight}{Volume} = [\frac{ML}{T^2L^3}] = [\frac{M}{T^2L^2}] \tag{5}$$

$$Z = Overburden\ Thickness = [L] \tag{6}$$

$$g = Gravity = [\frac{L}{T^2}] \tag{7}$$

$$S = Sectional\ Area = [L^2] \tag{8}$$

$$V = Seismic\ \ Wave\ Velocity = [\frac{L}{T}] \tag{9}$$

Two simplify the analyses two additional terms are introduced and expressed in terms of above variables; namely: **Dynamic Response Factor (R)** and **Load Capacity Factor (C)**.

- The **Dynamic Response Factor**, R, is defined as the ratio of the "equivalent modulus of deformability"-to-"seismic wave velocity" in the geologic system.

- The **Load Capacity Factor,** C, is defined as the ratio of "chamber loading density"-to-"overburden thickness."

In terms of dimensional quantities, R and C are expressed as:

$$R = \frac{E}{V} = \left[\frac{\frac{M}{LT^2}}{\frac{L}{T}} \right] = \left[\frac{M}{L^2 T} \right] \tag{10}$$

$$C = \frac{CHAMBER \ \ LOADING \ \ DENSITY}{OVERBURDEN \ \ THICKNESS} = \frac{K}{Z} = \left[\frac{M}{T^2 L^3} \right] \tag{11}$$

Equation (1) can now be written in terms of above parameters as

$$D = C_\alpha (R, \ C, \ S, \ g) \tag{12}$$

or

$$D = f \ (R^a \ C^b \ S^c \ g^d) \tag{13}$$

Equation (13) can be written in terms of dimensions of variables

$$M^0 T^0 L^1 = F \left[\frac{M}{L^2 T} \right]^a \left[\frac{M}{T^2 L^3} \right]^b [L^2]^c \left[\frac{L}{T^2} \right]^d \tag{14}$$

Since L on the left hand side of the Equation (14) has an implied exponent of one, T and M have implied exponents of zero, required and necessary equations are:

$$-2a - 3b + 2c + d = 1 \tag{15}$$

$$-a - 2b - 2d = 0 \tag{16}$$

$$a + b = 0 \tag{17}$$

Solution of the above auxiliary equations in terms of "d" reveal

$$a = 2d \qquad b = -2d \qquad c = (1-3d)/2$$

Using the above parameters, the Bakhtar's criteria, Equation (13) can be presented in its generalized form as:

$$D = \beta[(\frac{R}{C})^{2d} S^{\frac{1-3d}{2}} g^{d}] \tag{18}$$

where β and d are constants, they are determined using the data obtained from the physical modeling experiments conducted for the US Air Force to simulate KLOTZ tunnel explosion test in China Lake, California (Bakhtar, 1993c).

The simple mathematical expression shown above, Equation (18), represents the general form of the Bakhtar formulation of explosives safety criteria. The data from the Air Force scaled-model tunnel tests can be used in two different ways to derive two versions of the Equation (18) to predict:

(i) Range of hazardous fragments originating from accidental detonation of a responding magazine with a given loading density. This version is referred to as the "Loading Density - Fragment Range Relationship."

(ii) Distance at which more than one hazardous fragments are recovered per a given area from accidental detonation of a responding magazine. This version is referred to as the "Quantity-Distance Relationship" (Q-D).

For (ii), discussions are currently underway between the Air Force scientific consultant Colonel Edward Jacobs and the DDESB personnel for refinement of methodology (Jacobs, 1994) and its final form is not shown in this article. The relationships discussed in (i) and (ii) are derivatives from the Bakhtar Explosives Safety Criteria represented in its general form by the Equation (18).

Results reported for the field wave velocity measurements (Bakhtar, 1993c) and post-blast fragment survey investigation (Bakhtar, 1993d) were used to determine the constants "β" and "**d**" in Equation (18). Attention should be directed towards maintaining consistency in selecting proper units, i. e., selection of "g" values in English and International (SI) Systems result in 32.2 ft/sec^2 and 9.8146 m/sec^2, respectively. For purpose of this study the International (SI) system of measurements are used to determine the constants "β" and "d" in the Equation (18).

Data assigned to various parameters in the Equation (18) and their reference sources are shown in Table 6.

Substitution of the test data shown in Table 6 into the Equation (18) leads to formation of a set of auxiliary equations given by

$$\frac{6.45}{19.2} \times \frac{1}{\frac{66.4}{0.6096}}]^{2d} 0.0517^{\frac{1-3d}{2}} \times 9.8146^{d} = 122 \qquad (19)$$

and

$$\frac{651.2}{1{,}356.4} \times \frac{1}{\frac{16.6}{0.6096}}]^{2d} \times 0.0517^{\frac{1-3d}{2}} \times 9.8146^{d} = 48 \qquad (20)$$

Solving Equations (19) and (20) simultaneously results in values of β and d to be determined as:

d = -0.26 **β = 150**

Hence, the Bakhtar's Criteria for "Loading Density - Fragment Range" prediction based on the TNT equivalent weight of explosives, Equation (18) in Metric or SI (International) systems becomes simplified to a generalized form shown in Equations (21) and (22)

$$D = 150 \left(\frac{R}{C}\right)^{-0.52} S^{0.89} \times 9.8146^{-0.26} \qquad (22)$$

$$D = 150 \left(\frac{R}{C}\right)^{-0.52} * S^{0.89} * g^{-0.26} \qquad (22)$$

Where **S** is the "initial" venting characteristics or equivalent cross-sectional area of the access tunnel through which venting takes place, g is the acceleration due to gravity in SI or Metric System and is equal to 9.8146 m/sec^2 **, R** and **C** are the "dynamic response factor" and the "load capacity Factor," respectively. The Equation (22) is only valid for the responding tunnel in which internal detonation causes the overburden rock to break resulting in "total" venting through the cover.

The developed empirical expression, Equation (22), is examined by determining the fragment ranges based on the site specific data for the 20:1 scaled model tests conducted by Bakhtar (1993c) and KLOTZ Tunnel Explosion (the prototype) test in China Lake, California, reported by Halsey et al., (1989) . The results of observed and calculated fragment ranges are shown in Table 7.

TABLE 6. INPUT DATA - EQUATION (18)

TEST BED No.	EQUIVALENT MODULUS OF DEFORMABILITY (E) MPa (psf)	SEISMIC WAVE VELOCITY (V) m/sec (ft/sec)	GRAVITATIONAL ACCELERATION (g) m/sec^2 (ft/sec^2)	OVERBURDEN THICKNESS (T) m (ft)	CROSS-SECT. AREA (S)* m^2 (ft^2)	REFERENCE SOURCE
2	396.45 (8.28 x 10^6)	1,219.2 (4,000)	9.8146 (32.2)	0.6096 (2)	0.0517 (0.556)	Bakhtar (1993c)
4	651.20 (13.6 x 10^6)	1,356.4 (4,450)	9.8146 (32.2)	0.6096 (2)	0.0517 (0.556)	Bakhtar (1993d)

* - Venting Characteristics of Engineered System

NOTE: (1). RANGES AT WHICH HAZARDOUS FRAGMENTS WERE COLLECTED FOR TEST No. 2 AND No. 4 WERE 122-m (400-ft) AND 48-m (158-ft), RESPECTIVELY.

(2). OVERBURDEN DEPTH FOR 20:1 SCALED MODEL TESTS MEASURED AT CENTER OF CHAMBERS = 0.6096-m (2-ft).

(3). CHAMBER LOADING DENSITIES FOR TESTS 2 AND 4 WERE 66.4 kg/m^3 (4.15 lb/ft^3) AND 16.6 kg/m^3 (1.0375 lb/ft^3), RESPECTIVELY.

TABLE 6. INPUT DATA - EQUATION (18)

TABLE 7. COMPARISON OF CALCULATED AND OBSERVED FRAGMENT RANGES.

TEST DESCRIPTION	R* (MPa/m/sec.)	C+ (kg/m^4)	S++ (m^2)	OBSERVED RANGE■ (m)	CALCULATED RANGE■■ (m)
TEST #1 20:1 Scaled Model Tunnel Explosion (Bakhtar, 1993c)	0.4824	108.9231	0.0517	96	99
TEST #5 20:1 Scaled Model Tunnel Explosion (Bakhtar, 1993c)	0.4655	6.8077	0.0517	20	23
KLOTZ Tunnel Explosion Test (Halsey, et al., 1989)	2.1759	5.4462	20.68	2,011	1,982

*** - LOAD RESPONSE FACTOR = (EQUIVALENT MODULUS) / (SEISMIC WAVE VELOCITY)**
+ - LOAD CAPACITY FACTOR = (CHAMBER LOAD DENSITY) / (OVERBURDEN THICKNESS)
++ - VENTING CHARACTERISTICS = (CROSS-SECTIONAL AREA OF ACCESS TUNNEL
■ - HORIZONTAL DISTANCES MEASURED IN THE FIELD USING A COMPUTERIZED "TOTAL STATION"
■■ - CALCULATED BASED ON THE BAKHTAR CRITERIA, Equation (22)

TABLE 7. COMPARISON OF CALCULATED AND OBSERVED FRAGMENT RANGES.

In Table 7, the calculated range refer to those determined based on the Bakhtar's relationship (Equation 22). It can be deduced that the calculated hazardous fragment ranges are in excellent agreement (within less than ±3%) with those observed for the field scaled-model and prototype tests. Therefore, for accidental detonation in underground storage structures, Equation (22) can be used to calculate the TNT equivalent weight of the explosives stored once the range for blast-induced hazardous fragments are established. This technique has been applied recently to determine the quantity of explosives which caused the Steingletscher accident in the Swiss Alps (Bakhtar, 1994). Another application of this method is the prediction of hazardous fragment ranges from a responding magazine for different quantities of explosives. It should be understood that the accuracy of the calculations is contingent on the ability to acquire statistically acceptable site specific data on the index properties of the geologic and engineered systems. The input data to the Bakhtar Criteria, Equation (22), is obtained from index tests and a detailed discussion of such procedures are included in several reports submitted to the KLOTZ members and DOD personnel (Bakhtar, 1989); Bakhtar and Jenus (1994) .

5. CONCLUSION

As mentioned previously, the Bakhtar Explosives Safety Criteria and its associated characterization techniques for the geologic and engineered systems provide unique capabilities for design and safety assessment of the underground explosives storage structures. The main applications for responding magazines are:

- Loading Density Optimization
- Loading Density Calculations from Accident Yields
- Quantity-Distance (Q-D) Calculations
- Depth of Cover Calculations for Safe Storage of a Given Loading Density
- Sitting of Munitions Storage Facilities
- Overall Site Characterization - Civilian and Military

Published reports on the KLOTZ Tunnel Explosion Test in China Lake, California (Halsey, et al., 1989); the KLOTZ Tunnel Explosion Test Site in Älvdalen, Sweden (Bakhtar and Jenus, 1994); the Swiss Steingletscher Installation Accident (Bakhtar, 1994); Air Force Scaled-Model Tunnel Explosion Tests (Bakhtar, 1993a), are examples of site characterization, hazardous fragment range prediction , and the TNT equivalent explosives weight calculation for responding magazines using the described criteria.

Because safety of personnel, property, and equipment are the important considerations for the DOD munitions storage program, the criteria described in this paper provide a simple and cost-effective approach to accomplish those objectives. Such criteria can be applied for siting as well as the design and construction of next generation magazines or simply as a tool to evaluate the safety and assess the performance of the existing facilities.

6. ACKNOWLEDGEMENT

The work presented in this paper is part of an on-going research program on explosives hazards reduction study sponsored by the Department of Defense SBIR Phases I and II through a contract with the US Air Force. Mr. Joseph Jenus, Jr., from Air Force Operability Systems Management Office (YOX), is the Contract Manager, and Dr. Khosrow Bakhtar, from Bakhtar Associates, is the Principal Investigator.

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